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THESIS

THERMOMECHANICAL PROCESSING OF M-50 STEEL

by

Keith Robert Larson, Junior

June 1983

Thesis Advisor: T.R. McNelley

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Thermomechanical Processing of M-50 Steel

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ABSTRACT

Thermomechanical processing of AISI M-50 bearing steel was accomplished by an initial austenitize and quench followed by reheating and warm-rolling to a true strain of 2.0. Warm-rolling was successfully conducted at 650, 700, or 750°C. The effect of austenitizing temperature on grain size and residual carbides was evaluated following austenitizing at temperatures from 1090 to 1250°C. Grain growth was noted with increasing austenitizing temperature, especially for temperatures above 1150°C. Evaluation of the effect of warm-rolling on both carbide refinement and composition was performed using scanning electron microscopy. Comparison of as-received M-50 and the warm-rolled product were made. Temper carbides, those precipitated during the warm-rolling process, are refined by the processing. Residual carbides, those not dissolved in the initial austenitizing treatment, were only slightly refined in the rolling process. Stress-strain testing was conducted on both as-received and warm rolled materials and the increased strength observed were correlated with refined carbide and grain structures resulting from the warm-rolling.

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	8
	A. MATERIAL DESCRIPTION	9
	B. OBJECTIVES	11
II.	EXPERIMENTAL PROCEDURE	13
	A. AUSTENITIZING	13
	B. WARM-ROLLING	13
	C. MICROSCOPY	16
	D. MECHANICAL TESTING	17
III.	RESULTS AND DISCUSSION	18
	A. AUSTENITIZING TRIALS	18
	B. THERMOMECHANICAL PROCESSING	19
	C. MICROSCOPY	23
	D. SIGNIFICANCE OF RESIDUAL CARBIDES	24
	E. ANALYSIS OF RESIDUAL CARBIDES	27
	F. COMPARISON OF M-50 AND 52100	28
	G. HARDNESS	30
IV.	CONCLUSIONS	32
V.	RECOMMENDATIONS	33
LIST OF REFERENCES		46
INITIAL DISTRIBUTION LIST		47

LIST OF TABLES

		Page
I.	Mechanical Properties Warm-Rolled at 700°C.....	21
II.	Mechanical Properties Demonstrating Effect of Warm... Rolling Temperature	25
III.	Carbide Size Estimate.....	29
IV.	Hardness Data.....	31

LIST OF FIGURES

Page

1. Sample B Austenitized at 1225°C..... 34

2. Sample A Austenitized at 1250°C for thirty minutes.... 34

3. Sample B Austenitized at 1225°C for thirty minutes.... 35

4. Sample C Austenitized at 1200°C for thirty minutes.... 35

5. Sample D Austenitized at 1180°C for thirty minutes.... 36

6. Sample F Austenitized at 1140°C for thirty minutes.... 36

7. Sample G Austenitized at 1090°C (thirty minutes)..... 37

8. Sample AS-1 As-received material with large residual carbides on a background of temper carbides..... 37
9. Sample H Austenitized at 1150°C for five hours, warm-rolled at 700°C..... 38
10. Sample H X-ray scan of warm-rolled material, ten scans highlighting molybdenum..... 38
11. Sample H X-ray scan of warm-rolled material, 20 scans highlighting vanadium..... 39
12. Sample H X-ray scan of warm-rolled material, 5 scans highlighting iron..... 39
13. Sample H X-ray scan of warm-rolled material, 20 scans highlighting chromium..... 40
14. Sample AS-2 As-reveived material, residual carbides on a background of temper carbides..... 41
15. Sample AS-2 X-ray scan of as-received material, ten scans highlighting molybdenum..... 41
16. Sample AS-2 X-ray scan of as-received material, twenty scans highlighting vanadium..... 42
17. Sample AS-2 X-ray scan of as-received material, five scans highlighting iron..... 42
18. Sample AS-2 X-ray scan of as-received material, twenty scans highlighting chromium..... 43
19. As-received material showing residual carbides on a background of temper carbides..... 44
20. Material austenitized at 1150°C for five hours, warm-rolled at 650°C..... 44
21. Material austenitized at 1150°C for five hours, warm-rolled at 700°C..... 45
22. Material austenitized at 1150°C for five hours, warm-rolled at 750°C..... 45

I. INTRODUCTION

Thermomechanical processing of AISI M-50 steel is one of several avenues of investigation in the search for possible improvements in gas turbine roller bearings. Thermomechanical processing combines the effects of controlled thermal and mechanical history of the steel to produce a fine dispersion of carbide particles in a fine grained matrix. The Naval Postgraduate School research into the effects of thermomechanical processing is built on a foundation established by Sherby and co-workers [Ref. 1] at Stanford University. Sherby's work in the field of superplasticity in high and ultra high carbon steel has resulted in a method to produce a highly refined structure (ferrite grain size less than 1.0 um and carbide size 0.1-0.5 um) in such steels, with substantial improvements in mechanical properties.

Investigation into the effect of thermomechanical processing of 52100 at the Naval Postgraduate School is reported by McNelley, et. al. [Ref.2] Isothermal rolling of samples subject to different initial heat treatments produced highly refined carbides in comparison to the as-received condition and improvement in yield strength. Two significant findings concerning residual carbides, carbides not completely taken into solution in an initial austenitizing treatment, were reported. First, residual carbides are only

slightly reduced by subsequent warm-rolling at 650°C; secondly, all residual carbides can be dissolved in 52100 with proper austenitizing treatment. The residual carbides were taken into solution by austenitizing at 1000°C. From this temperature, the steel was either quenched to produce martensite or air cooled to produce pearlite. Pearlitic starting structures were not completely spheroidized by warm rolling and a lower in room temperature ductility was noted. Tempered martensite structures result in more uniform structures after rolling. As noted by McNelley et. al., this type of thermomechanical processing results in a material with a refined ferrite-carbide microstructure, it is an intermediate process. The resulting microstructure is too soft for the intended application as a bearing; in application it would be necessary to employ a final heat treatment to harden the material. Austenitizing, quench, and temper would be required to take full advantage of the microstructural refinement. It has been demonstrated that microstructural refinement can be maintained through the hardening process in work with 52100.

A. MATERIAL DESCRIPTION

AISI M-50 is a specialty tool steel which finds application in gas turbine engine bearings and spur gears. The material is produced using vacuum induction melting followed by vacuum arc remelting (VIM VAR) process. Improved cleanliness and composition

control achieved through advances in manufacturing techniques have been documented by Anderson and Zaretsky [Ref. 3] as leading to five fold increases in bearing life over air melted M-50 products. Bar stock of one inch (25.4 mm) diameter, centerless ground, in the spheroidize-annealed condition was used throughout this research.

Work with AISI 52100 demonstrated that residual carbides could be completely taken into solution by a high temperature (1000°C) austenitizing treatment. Excess residual carbides are to be expected in M-50. The analysis of the composition of these residual carbides, their response to warm rolling, and their effect on mechanical properties was analyzed in a series of experiments. The refinement of grain size and temper carbides was also examined.

A typical composition for M-50 is:

C	Mn	Si	Cr	Mo	V
0.80	0.30	0.25	4.10	4.25	1.10

Extensive analysis of carbide solutioning in M-50 is reported by Bridge, Maniar and Philip [Ref. 4]. The carbides of M-50 are reported to be of four types: $M_{23}C_6$, M_6C, M_2C, and MC. Solvus temperatures are reported for $M_{23}C_6$ as 1820°F (990°C) and for M_6C 1990°F (1090°C). Residual carbides of the M_2C and MC variety could not be completely driven into solution. Residual or excess carbides were present at the level of three to five volume percent following high temperature austenitizing treatment. Precipitation

of $M_{23}C_6$ in the range 300 to 800°F (150 to 425°C) is characteristic of tempering in M-50. Secondary hardening is reported during the 800° F (425°C) temper. There appears to be a metastable phase of M_2C, rich in molybdenum, which solutions at high temperatures. Localized enrichment in molybdenum facilitates precipitation of M_6C carbides.

Carbide analysis reported by Bridge et. al. [Ref.4] indicate MC carbides are nearly all VC. M_2C carbides range from $(Mo_{0.70}\ Fe_{0.14}\ Cr_{0.15})_2\ C$ to $(Mo_{0.27}\ Fe_{0.41}\ Cr_{0.32})_2\ C$ with increased tempering temperature. $M_{23}\ C_6$ is a chromium-rich carbide. $M_6\ C$ in M-50 is a molybdenum-rich iron carbide.

In contrast, a plain carbon steel with 0.80 percent carbon would have two phases present at room temperature: ferrite, body centered cubic iron, and Fe_3C. AISI 52100 has a slightly higher carbon content than M-50 but is less heavily alloyed. The principal additions are 1.35 pct. Chromium and 0.36 pct. Manganese. AISI 52100 bearings operated at normal ambient temperatures are superior to M-50 bearings. The more heavily alloyed M-50, however, is superior for elevated temperature applications as it resists softening at elevated temperatures much better than 52100.

B. OBJECTIVES

Research in thermomechanical processing of M-50, supported by the Naval Air Propulsion Center, Trenton, New Jersey, is designed

to incorporate the findings of the Naval Postgraduate School research on 52100 and expand on it with a similar study of thermomechanical processing of M-50.

The objective of the investigation into thermomechanical processing of M-50 is fourfold:

1) Determine if M-50 can be successfully warm-rolled.
2) Examine the effects of thermomechanical processing on microstructure.
3) Analyze the dependence of mechanical properties of a warm-rolled product on austenitizing and warm-rolling temperatures.
4) Compare and contrast M-50 and 52100 findings.

Subsequent work will investigate the effect of final heat treatment to achieve bearing hardness while retaining a refined microstructure.

II. EXPERIMENTAL PROCEDURE

A. AUSTENITIZING

A series of experiments was conducted to evaluate the effect of austenitizing temperature on grain size and dissolution of residual carbides. Austenitizing temperatures examined were 1090, 1140, 1160, 1180, 1200, 1225, and 1250°C. Samples were coupons transversely sectioned from one inch (25.4 mm) diameter bar, to a thickness of 0.375 inch (9.5 mm). Samples were wrapped in 0.005 inch (0.13mm) thick nickel foil with a piece of titanium sponge included as an oxygen getter. Samples were soaked initially at 870°C for a minimum of thirty minutes, then austenitized for thirty minutes.

In a separate experiment, austenitizing time at 1180°C was varied from two to twenty hours. Samples again were preheated at 870°C and then heated to 1180°C for two, five or twenty hours. An additional sample was heated in the furnace for four thirty minute periods with a one hour air cool between furnace exposures.

B. WARM-ROLLING

Warm-rolling was carried out at three temperatures: 650, 700, and 750°C. Sections of bar stock 4.0 inches (100 mm) in length were wrapped in nickel foil with titanium sponge added as before. Five samples were prepared for warm-rolling at 700°C. Samples were

austenitized at 1100°C and 1140°C for five hours following a one hour soak at 870°C. Three samples were austenitized at 1180°C; the first for one hour, the second for three one-hour exposures with one-hour air cool between exposures, and the third was austenitized at 1180°C for five hours. All five were quenched into a 620°C salt bath at the end of the austenitizing treatment. Following the salt quench, samples were air cooled.

Initial warm-rolling was accomplished at 700°C. Rolling passes of 0.08 inch (2.0 mm) had been accomplished in preliminary research; however the rolling mill stalled at this reduction and reduction per pass was decreased to 0.04 inch (1.0 mm). Rolling the one inch diameter sections to a final nominal thickness of one tenth of an inch was accomplished in twenty-seven passes of 0.04 down to 0.01 inches on the final three passes. The reduction in thickness per pass was thereby maintained at a maximum of fifteen percent per pass. In all cases, the samples were reheated between each rolling pass to maintain isothermal conditions. Total time at warm-rolling temperature ranged from 10 to 21 hours.

Warm-rolling was carried out at two additional temperatures, 650 and 750°C. Samples were soaked at 870°C, austenitized at 1150°C for five hours, quenched into a salt bath at 620°C, and allowed to air cool were then reheated and rolled at 650°C or

750°C. A sample was similarly prepared but austenitized at 1225°C for five hours and warm-rolled at 750°C.

Difficulties arose on the first attempt to warm-roll at 650°C. The sample austenitized at 1180°C (5 hours) was allowed to soak at 650°C for two and one half hours. On the fifth rolling pass, the sample cracked at the entry end in the mill. Upon subsequent examination of the sample a hairline crack was discovered along nearly the entire length of the specimen. Previous experience in attempting to warm roll such steel in this laboratory discovered an apparent level of hardness at 40 Rockwell "C" below which warm-rolling can be successfully accomplished.

The hardness of this cracked sample following approximately three and one half hours at 650°C was Rockwell "C" 42.5-45. The cracked sample was then cut into two sections and given further tempering at 650°C. Hardness testing was accomplished on the two pieces at various time intervals. Hardness readings below the R_C 40 level (R_C35.5-39) were achieved at approximately twelve hours of tempering.

A sample was then austenitized at 1150°C for five hours, salt quenched at 620°C and allowed to air cool. The specimen was tempered at 650°C for eleven hours, then water quenched and tested for hardness. Rockwell "C" hardness readings in the range of 26-30 were obtained, indicating that a shorter continuous tempering time

may be expected to reduce hardness to a satisfactory level. The sample was allowed one and one half hours at 650°C and warm-rolling was commenced. Warm-rolling proceeded smoothly until a mill setting to 0.240 from 0.280 inches. The rolling pass at 0.240 stalled the mill. The sample was extracted from the mill and allowed to soak for one hour at 650°C. The sample was then rolled 0.240 and the reduction per pass was decreased to 0.02 inches. Rolling proceeded smoothly and was accomplished in a total of thirty rolling passes. Tensile specimens (subsize) were prepared from all warm-rolled products.

C. MICROSCOPY

Optical microscopy proved most suited to the analysis of grain size and residual carbide distribution in material which had been austenitized and allowed to air cool. Specimens were cut from the round coupons by halving then quartering one half. Specimens were mounted in bakelite and polished using wet emory cloth followed by diamond polishing wheels. Villea's reagent was used to reveal grain boundaries.

The scanning electron microscope was employed to attempt to resolve grain size of the warm-rolled products and examine the precipitated carbides. X-ray scans of as received material and a warm-rolled product were made for molybdenum, vanadium, chromium, and iron.

D. MECHANICAL TESTING

Hardness data was collected for all samples using a Wilson Model 1-JR Rockwell hardness tester. Tensile test specimens were machined from as-received material and from all warm-rolled material. ASTM subsize tensile specimens were machined to 0.25 inch (6.4mm) width with a nominal as-rolled thickness of 0.1 inch (2.5mm) and a one inch (25.4mm) gage length. Tensile testing was conducted on an Instron Model TTD Universal Testing Instrument with a 0.2 inch per minute crosshead speed. Load-elongation data was autographically recorded and analyzed to obtain yield and ultimate tensile strength data. Elongation data was obtained in the usual manner from fractured test pieces.

III. RESULTS AND DISCUSSION

A. AUSTENITIZING TRIALS

Initial austenitizing trials were conducted at 1250, 1225, and 1200°C for thirty minutes. Examination of the specimens under the optical microscope revealed large grain size and the presence of residual carbides. Indications of partial melting were also present in all three specimens. The lamellar structure resulting from partial melting at a grain boundary triple point, is highlighted in Figure 1. Micrographs of the samples austenitized at 1250, 1225, and 1200°C are presented in Figures 2-4. Residual carbides are the small, white, irregularly shaped areas within the grains. Indications of partial melting can be detected in all three micrographs. Concern about the effects of partial melting on the properties of the warm-rolled product led to investigation of a lower range of austenitizing temperatures. One sample austenitized at 1225°C for 5 hours was warm-rolled at 750°C. Mechanical properties of this sample will be compared to other warm-rolled products.

Concern for possible deleterious effects on properties of the partial melting lead to investigation of lower austenitizing temperatures. A second set of austenitizing trials, therefore, was conducted at lower temperatures: 1180, 1160, 1140, and 1090°C. Heating time at these temperatures was thirty minutes.

Representative micrographs from these specimens are presented in Figures 5-7. Grain growth with increasing austenitizing temperature is obvious, especially for samples austenitized above 1140°C. Residual carbides are evident in all samples; however, evidence of partial melting is not indicated. The decision to investigate the effects of austenitizing time at 1180°C was based on the apparent absence of partial melting at this temperature as well as to the goal to dissolve the maximum amount of carbon possible.

Samples were heated for two, five, and twenty hours at 1180 °C. An additional sample was exposed to the 1180°C furnace for four 30-minute periods with a one hour air cool between exposures. Heavy oxidation on the surface of the twenty hour sample rendered it useless and attempts to austenitize beyond five hours were abandoned. Residual carbides were still present following five hours at 1180°C but no indications of partial melting were present.

B. THERMOMECHANICAL PROCESSING

After the initial heat treatment, the second step in the thermomechanical processing was the warm-rolling. This was conducted at three temperatures: 650, 700, or 750°C, and the initial warm-rolling trials were conducted at 700°C. For this five samples were austenitized as follows:

1) 1100°C (5 hours)

2) 1140°C (5 hours)

3) 1180°C (5 hours)

4) 1180°C (1 hour)

5) 1180°C 3 (1 hour)
(with intermittent 1 hour air cool)

Warm-rolling at 700°C proceeded without difficulty. Subsize tensile specimens were machined from the warm-rolled products. A summary of the ultimate tensile strengths and elongations are presented in Table I and a trend of increasing ultimate tensile strength with increasing austenitizing temperature is noted.

Warm-rolling at 750°C was conducted on two samples. The first was austenitized at 1150°C for five hours, the second at 1225°C, also for five hours. The warm-rolling of material which had indication of partial melting (1225°C, five hours) resulted in a product with good strength and also a greater than that of the material rolled under identical warm-rolling conditions but initially austenitized at a lower temperature.

As-received material exhibited an ultimate tensile strength of 100,100 psi with an elongation of 22 percent. The ultimate tensile strength of the 1225°C (5 hour) material was 145,300 psi with an elongation of 15 percent.

TABLE I

MECHANICAL PROPERTIES
WARM-ROLLED AT 700 DEGREES CENTIGRADE

Austenitizing Temperature °C (Time) Warm-Rolling Temperature
Ultimate Tensile Strength
Percent Elongation

1100 (5 hours) WR 700
140,300 psi
10%

1180 (1 hour) WR 700
143,400 psi
11%

1140 (5 hours) WR 700
144,600 psi
10%

1180 Intermittent 3 (1hour) WR 700
153,400 psi
7%

1180 (5 hours) WR 700
150,900 psi
8%

The evaluation of the effect of warm-rolling temperature was continued by warm-rolling an 1150°C (5 hour) sample at 650°C. Difficulties with warm-rolling at 650°C without sufficient tempering are detailed in the Experimental Procedure Chapter. Results of the tensile testing over a range of warm-rolling temperatures are given in Table II. Mechanical properties after warm-rolling reflect the finer microstructures produced by warm-rolling at lower temperatures. Ultimate tensile strength was observed to increase as warm-rolling temperature decreased. Tempering alone at lower temperatures would result in increased strength. Previous work [Ref. 2] on 52100 has shown that the warm-rolling results in highly refined grain size as well as the retention of a fine size of temper carbide. The grain size refinement was the result of recrystallization during the rolling process. Rolling at lower temperatures would be expected to result in a finer grain size by this mechanism and also a lessened growth of temper carbides and thereby a finer overall microstructure. Finally, the finer microstructure would result in a higher strength material as observed here in this work on M-50.

Especially notable was the ductility and strength of the 1225°C (5 hour) sample. Optical microscopy had indicated that partial melting had occurred. Insufficient data is available to

draw specific conclusions, but the extent of partial melting present does not appear to seriously impair material characteristics.

C. MICROSCOPY

Examination of the warm-rolled products with the optical microscope revealed residual carbides remained after warm-rolling but the grain size and the size of the temper carbides could not be resolved. Residual carbides in all samples except the 1225°C (5 hours) maintained the same morphology as those in the austenitized and quenched samples. The 1225°C (5 hours) and warm-rolled sample, however, exhibited a flattening or stringing out of the residual carbides in the rolling direction.

Scanning elecron microscopy was employed in an attempt to resolve grain size and examine the refined carbides. This was not entirely successful but a great deal of information was revealed concerning both residual and temper carbides. Scanning electron micrographs of the as-received material are shown in Figure 8. Large residual carbides are shown on a background of smaller, temper carbides. The effect of warm-rolling on these carbides is revealed in Figure 9. Residual carbides are reduced in size to a small extent in warm-rolling. The temper carbides are much finer than the 0.5 - 3.0 um spheroidized carbides in the as-received material.

After warm-rolling at 700°C, these carbides are of a size ranging from less than 0.1um up to about 1.0um. Temper carbides in 650°C warm-rolled material range in size from less than 0.1 to 0.4 micron. A comparison of as received material with the 650°C warm-rolled product is displayed in Figure 19 and Figure 20. Similar, refined carbides were observed in the previous work on 52100 [Ref. 2]. This refinement of the temper carbides relative to their precursors is related to at least two factors. First, their precipitation as fine temper carbides from a supersaturated martensite and second, to the effects of the warm-rolling in providing nucleation sites for further precipitation and also in shearing of large precipitates to break them up into finer particles. The effect of tempering alone for times similar to those required to accomplish the warm-rolling was not investigated here but should be evaluated.

D. SIGNIFICANCE OF RESIDUAL CARBIDES

Residual carbides in M-50 cannot be fully driven into solution and they are only slightly refined in warm-rolling. Rescalvo and Averbach [Ref. 5] conclude, however, that undissolved carbides do not greatly affect fatigue crack growth behavior of M-50. Further, they state that at usual hardness levels for bearing applications, the plane strain fracture toughness and fatique crack propagation rates in M-50 are apparently controlled by the ductility of the

TABLE II

MECHANICAL PROPERTIES
DEMONSTRATING EFFECT OF WARM-ROLLING TEMPERATURE

Austenitizing Temperature °C (Time) Warm-Rolling Temperature
Ultimate Tensile Strength
Percent Elongation

As received 100,100 psi 22%		1225 (5 hours) WR 750 145,300 psi 15%
1150 (5 hrs.) WR 650 195,500 psi 7%	1140 (5 hrs.) WR 700 144,600 psi 10%	1150 (5 hrs.) WR 750 141,400 psi 9%

matrix and are relatively insensitive to the volume, sizes, and distribution of undissolved carbides. On the other hand, Coquillet and Guiraldenq [Ref. 6], working with electroslag remelted (ESR) M-50 in rotating beam fatique tests, found both non-metallic inclusions and undissolved carbides at the origin of failure. Thirty micron diameter MC and M_6C carbides were found to have the same debilitating effect as ten micron diameter aluminates. These different observations may result in part from the different measurements being made. In the first case, only crack growth rates measured and, given the relatively low fracture toughness of such materials, the size of the plastic zone at the crack tip may be sufficiently small that it does not interact strongly with the large carbides. Instead, the matrix alone principally governed cracking. Rotating beam tests in the second case would involve initially uncracked materials. Here, crack initiation as well as crack growth would affect the fatigue life and initiation would be expected to occur at discontinuities such as oxide inclusions or coarse, residual carbides. Some refinement of the residual carbides is noted in this research and this processing may enhance resistance to crack initiation. The refined matrix of ferrite and temper carbides would be expected to result in a refined matrix when heat treated and thus enhance resistance to crack growth.

E. ANALYSIS OF RESIDUAL CARBIDES

The scanning electron microscope was used to analyze the constituents of residual carbides in the as received material and warm-rolled product. Two distinct types of residual carbides were revealed by X-ray scanning for molybdenum and then vanadium. Photomicrographs of 700°C warm-rolled product are shown in Figures 9 through 13. Residual carbides on a background of temper carbides in Figure 9 were scanned for molydenum, vanadium, iron, and chromium, and the results are shown in Figures 10 through 13 respectively. Molybdenum is present in all residual carbides as is vanadium. Two distinct residual carbides do appear in the photomicrographs. Concentrations of vanadium indicated the presence of VC whereas concentration of molybdenum indicates the presence of Mo_2C. A lessened iron concentration in the residual carbides is noted. The uniformity of the chromium distribution indicates that chromium substitutes equally in residual as well as temper carbides.

A series of photomicrographs of the as-received material is displayed in Figures 14 through 18. The patterns of uniform chromium content and lessened iron content in residual carbides, and the distinct concentrations of vanadium and molybdenum in residual carbides are again apparent. Focusing the scanning electron microscope on a field of temper carbides revealed a uniform distribution

of the four elements for which scans were made. Analysis of small (about 2.0 um) residual carbides at a magnification of 12000X revealed the same characteristics of molybdenum, and vanadium enrichment, lessened iron content and a uniform distribution of chromium. Estimates of residual and temper carbide size are given in Table III. Photomicrographs of as-received material and products warm-rolled at 650°C, 700°C or 750°C are shown in Figures 19 to 22.

F. COMPARISON OF M-50 AND 52100

The work on 52100, which contains a single $(Fe, Cr)_3C$ carbide, showed that residual carbides could be eliminated by a high temperature (1,000°C) initial austenitizing treatment. M-50, on the other hand, has a complex series of carbides and in particular, VC and Mo_2C, which cannot be dissolved at any temperature below the melting point. Hence, the M-50 contains residual carbides which are reduced in size by warm-rolling but only to a limited extent. Both materials are similar with regard to production of refined temper carbides. In both cases, carbides are refined to sizes at least as small as 0.1um. The effect of the processing on grain size has not yet been determined for M-50 but is thought to result in similar refinement to the submicron grain size produced in rolling of the 52100, based on the relatively high tensile strength obtained after warm-rolling.

TABLE III

CARBIDE SIZE ESTIMATE

As-received	
Temper carbides	0.5 to 3.0 micron
Residual carbides	up to 18 micron
Warm-rolled 650°C	
Temper carbides	Less than 0.1to 0.4 micron
Residual carbides	up to 10 micron
Warm-rolled 700°C	
Temper carbides	Less than 0.1 to 1.0 micron
Residual carbides	up to 10 micron
Warm-rolled 750°C	
Temper carbides	Less than 0.1 to 1.0 micron
Residual carbides	up to 7 micron

Finally, M-50 may be rolled at relatively higher temperatures and still allow achievement of a fine microstructure. This is the result of alloying and the increase in the apparent eutectoid temperature to values above 750°C. This difference in eutectoid temperature was employed here in rolling at 750°C, a temperature where 52100 would contain austenite rather than ferrite.

G. HARDNESS

Hardness as a characteristic in roller bearing application has experienced an evolutionary development. Initial evaluations indicated that harder was better. Later findings stated that an optimum hardness could be employed and that maximum attainable hardness was not optimal. Latest research now indicates that bearing life may be more dependent on a differential in hardness of one to two points Rockwell "C" hardness between the rollers and the race over a range of hardness conditions for both components [Ref. 3].

Hardness for materials austenitized at various temperatures for thirty minutes (air cool) is presented in Table IV. Extensive work in the heat treatment of M-50 is presented by Schlict [Ref. 7] A wide range of material hardness and matrix ductility is possible. Trade offs are required to determine suitable heat treatment, the critical type of stressing of a rolling bearing must be known. Investigation of the heat treatment response of thermomechanically processed M-50 will be undertaken in future research.

TABLE IV

HARDNESS DATA

Austenitizing Temperature ^{o}C (Time)	Hardness Rockwell "C"
1250 (1/2 hour) Air Cool	51.5 - 56.5
1225 (1/2 hour) Air Cool	58 - 60
1200 (1/2 hour) Air Cool	52 - 56
1180 (1/2 hour) Air Cool	59 - 62
1160 (1/2 hour) Air Cool	59 - 64.5
1140 (1/2 hour) Air Cool	56 - 64
1090 (1/2 hour) Air Cool	59 - 64.5
1150 (5 hours) Salt Bath Quench 615°C	65 - 66
1225 (5 hours) Salt Bath Quench 615°C	55 - 56.5

IV. CONCLUSIONS

1) AISI M-50 can be successfully warm-rolled in the range of 650 to 750°C.

2) This processing results in a much refined structure relative to the spheroidize-annealed, as-received condition.

3) Residual carbides (MC, M_2C) cannot be fully solutioned in M-50 and are only slightly refined in warm-rolling.

4) The processing produces a material with a higher ultimate tensile strength than the as-received material.

5) Austenitizing temperature is secondary to warm-rolling temperature in contribution to ultimate tensile strength.

6) Two distinct residual carbides exist in M-50; one rich in molybdenum, the second rich in vanadium.

V RECOMMENDATIONS

1) Transmission electron microscopy should be employed to resolve grain size and gain further insight into carbide refinement of thermomechanically processed M-50.

2) The heat treatment response of thermomechanically processed M-50 should be investigated in future research.

3) The effect of tempering alone on the temper carbide size should be examined to better determine the separate effects of warm-rolling and tempering.

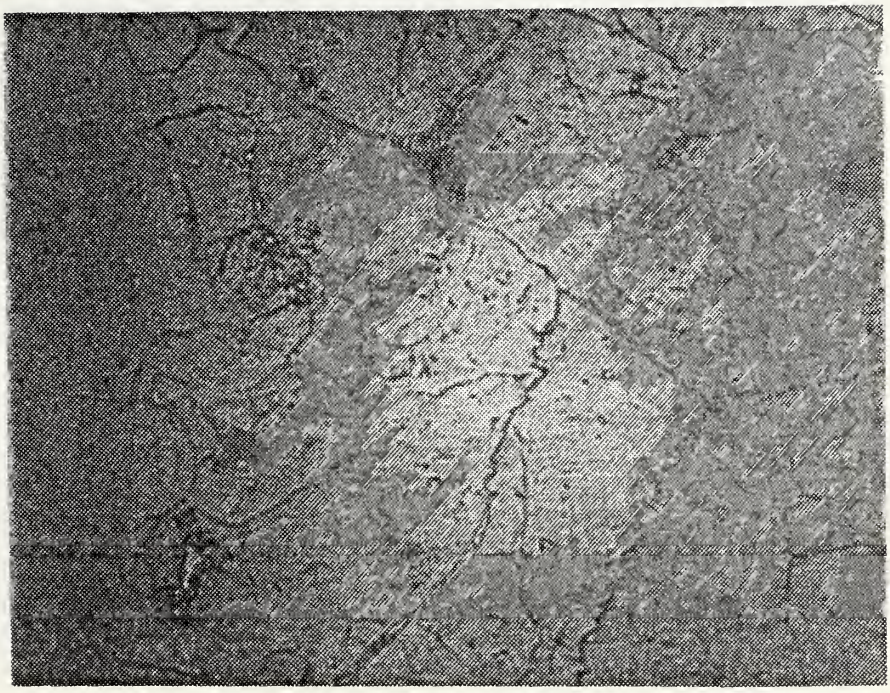

Fig. 1 Sample B Austenitized at 1225°C. (thirty minutes) Indication of partial melting at grain boundaries. Magnification 650X

Fig. 2 Sample A Austenitized at 1250°C for thirty minutes. Magnification 250X

Fig. 3 Sample B Austenitized at 1225°C for thirty minutes. Magnification 250X

Fig. 4 Sample C Austenitized at 1200°C for thirty minutes. Magnification 250X

Fig. 5 Sample D Austenitized at 1180^{0}C for thirty minutes. Magnification 250X

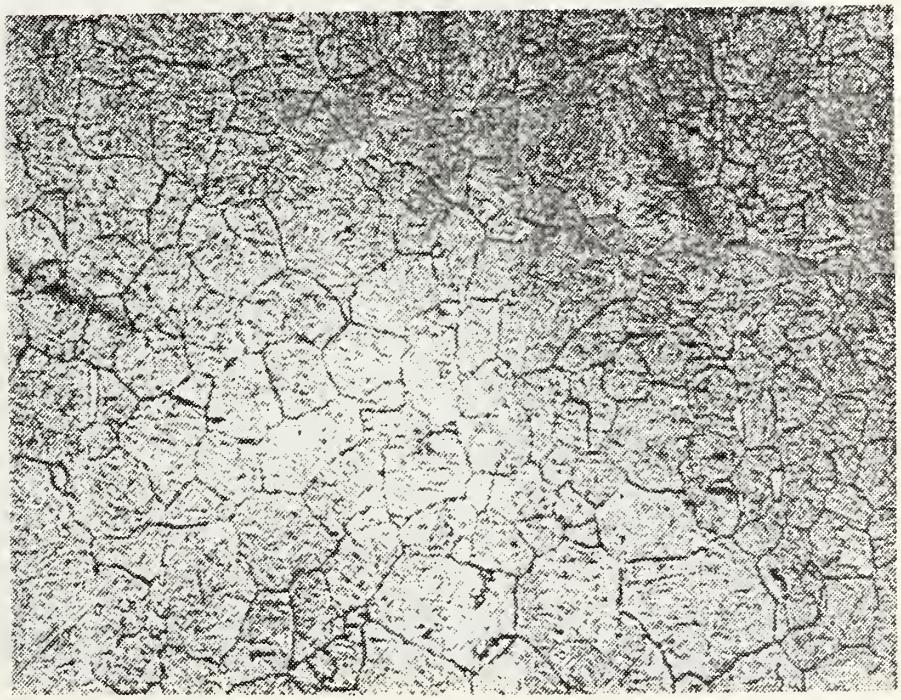

Fig. 6 Sample F Austenitized at 1140°C for thirty minutes. Magnification 250X

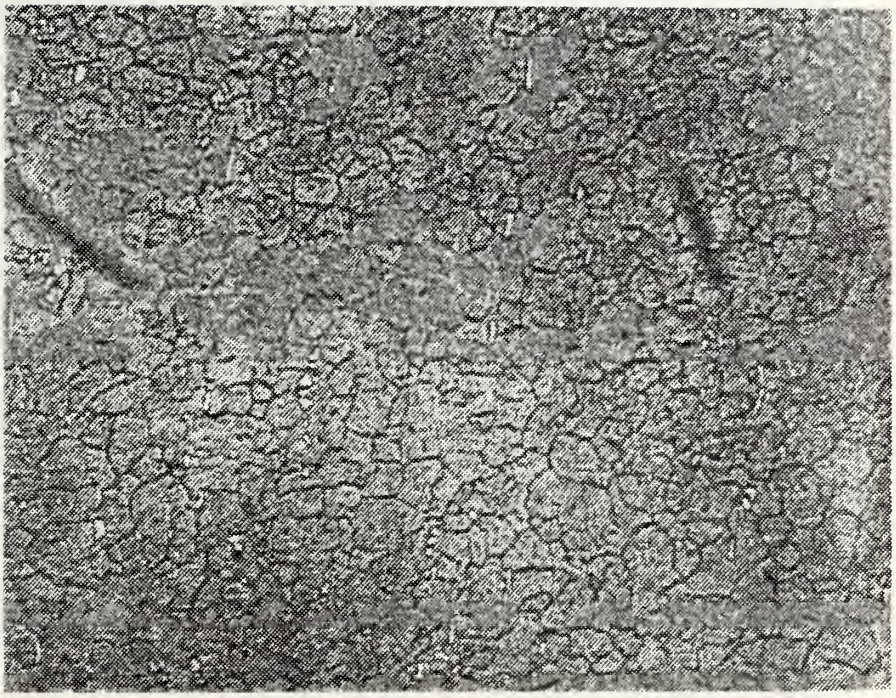

Fig. 7 Sample G Austenitized at 1090°C (thirty minutes). Magnification 250X

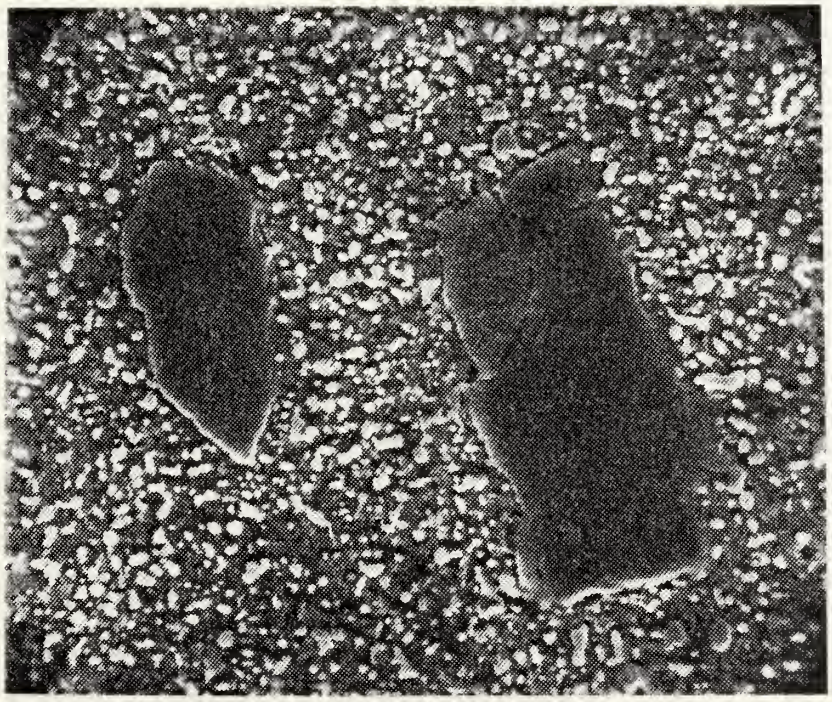

Fig. 8 Sample AS-1 As-received material with large residual carbides on a background of temper carbides. 2400X

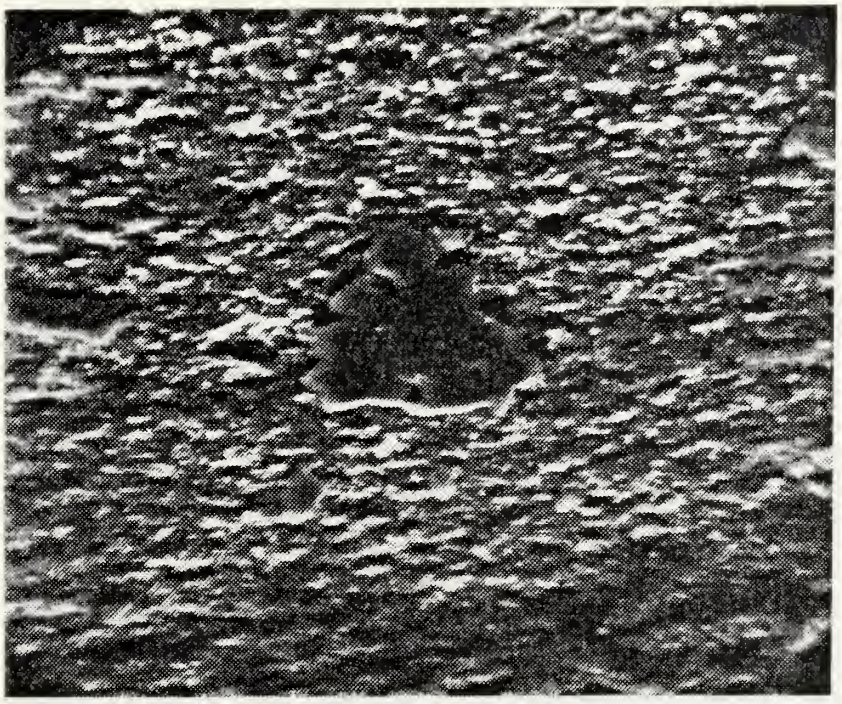

Fig. 9 Sample H Austenitized at 1150°C for five hours, warm-rolled at 700°C. Residual carbide on a background of finely dispersed temper carbides. Magnification 2200X

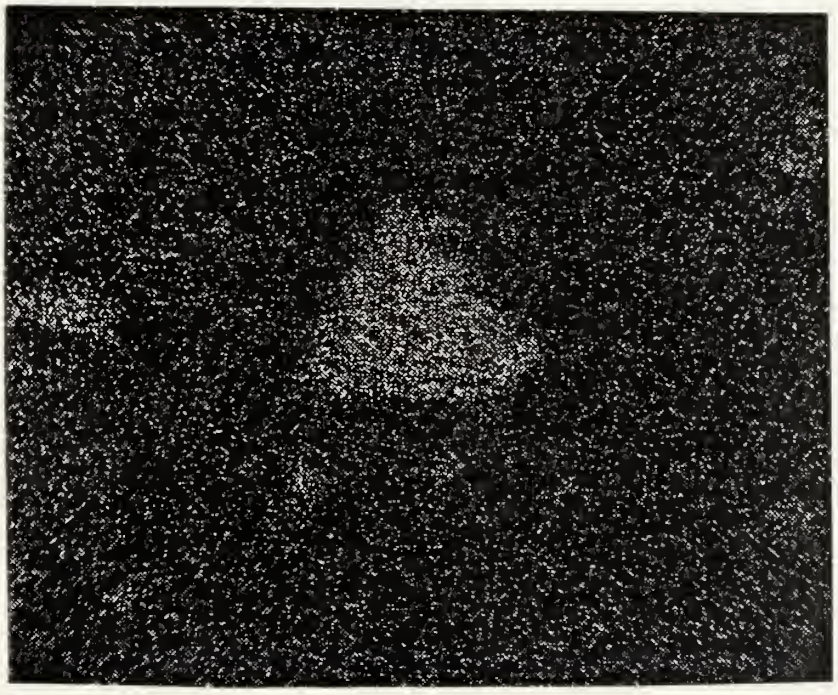

Fig. 10 Sample H X-ray scan of warm-rolled material, ten scans highlighting molybdenum. Magnification 2200X

Fig. 11 Sample H X-ray scan of warm-rolled material, 20 scans highlighting vanadium. Magnification 2200X

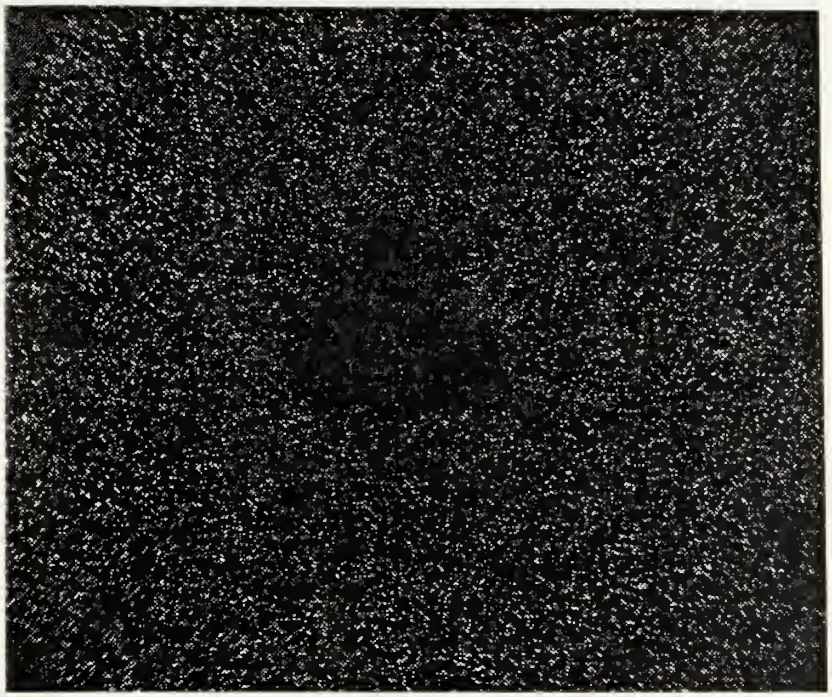

Fig. 12 Sample H X-ray scan of warm-rolled material, 5 scans highlighting iron. Magnification 2200X

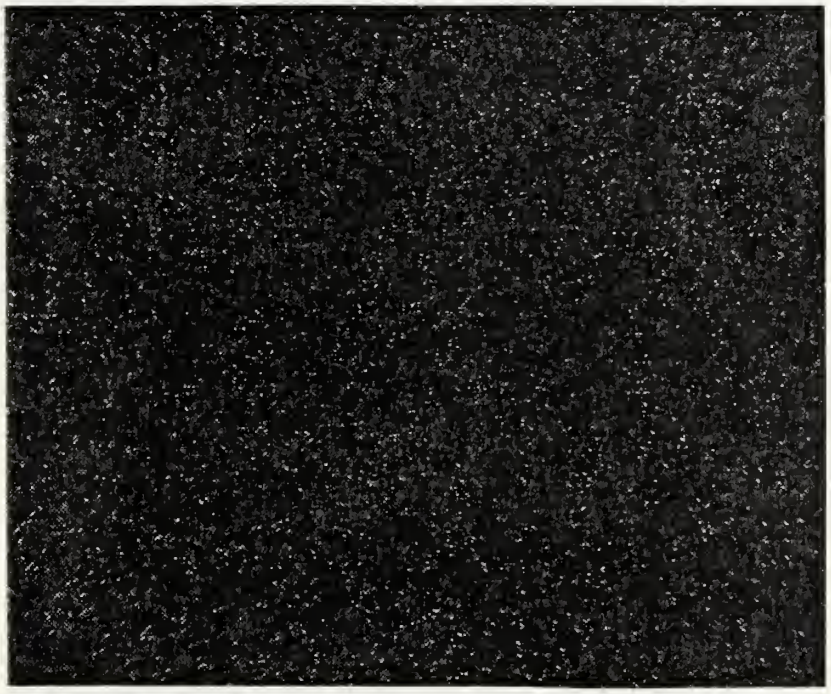

Fig. 13 Sample H X-ray scan of warm-rolled material, 20 scans highlighting chromium. Magnification 2200X

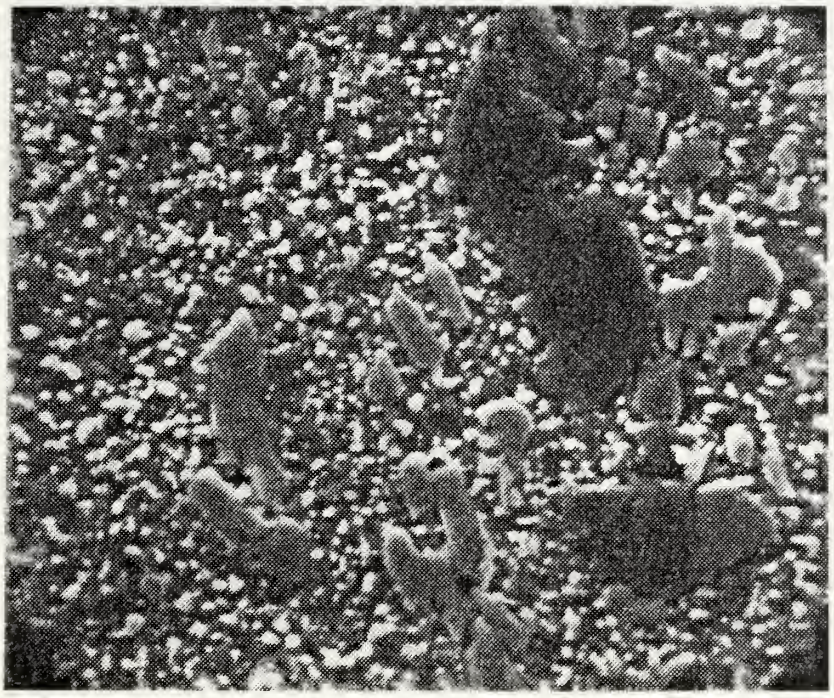

Fig. 14 Sample AS-2, As-received material, residual carbides on a background of temper carbides. Magnification 2400X

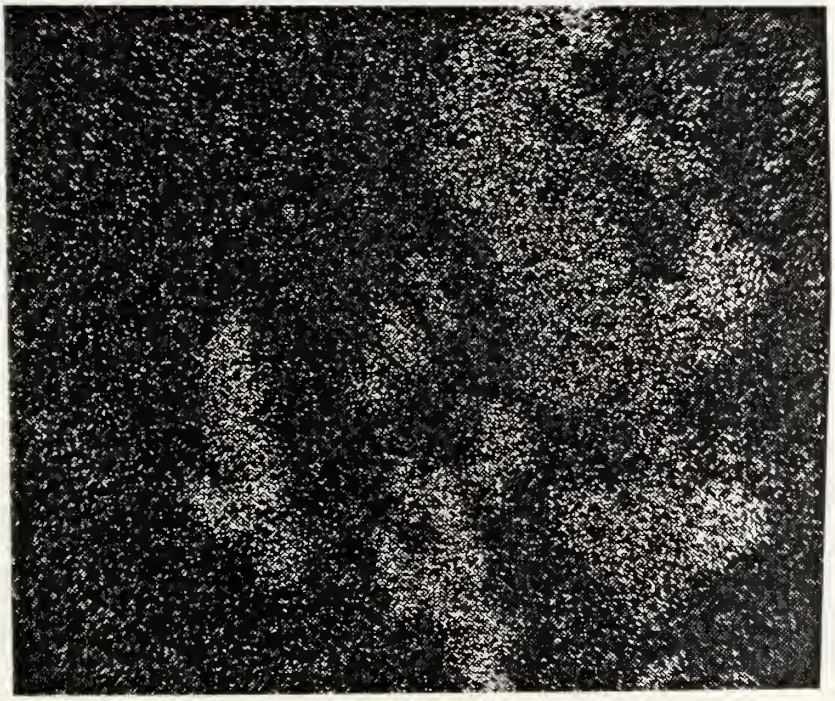

Fig. 15 Sample AS-2 X-ray scan of as-received material, ten scans highlighting molybdeum. Magnification 2400X

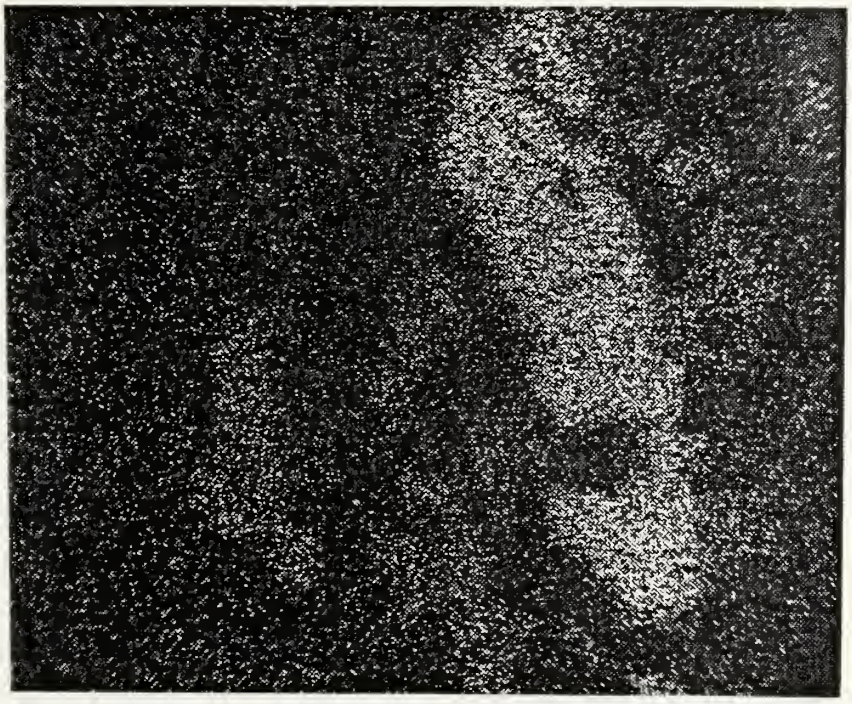

Fig. 16 Sample AS-2 X-ray scan of as-received material, twenty scans highlighting vanadium. Magnification 2400X

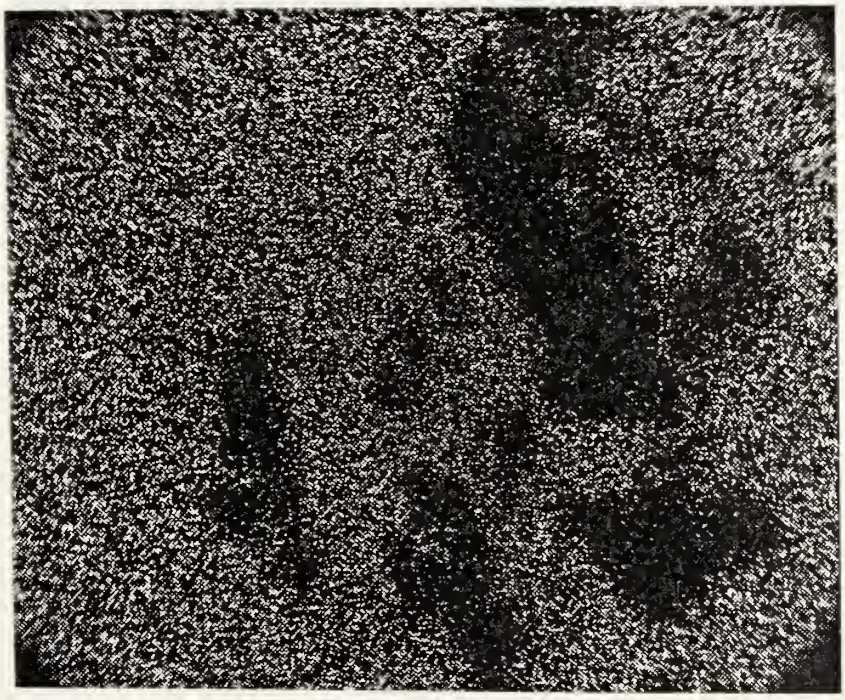

Fig. 17 Sample AS-2 X-ray scan of as-received material, five scans highlighting iron. Magnification 2400X

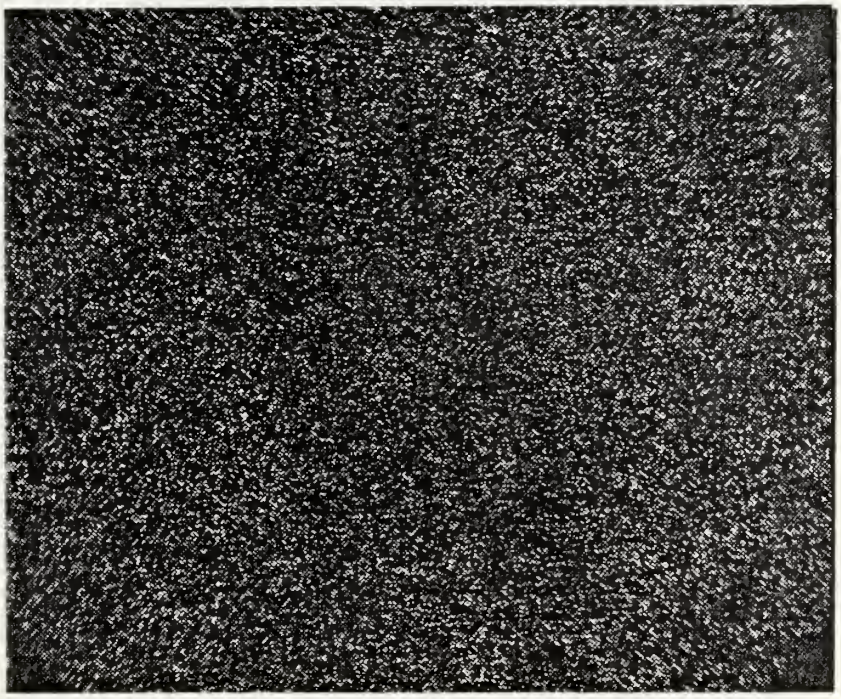

Fig. 18 Sample AS-2, X-ray scan of as-received material, twenty scans highlighting chromium. Magnification 2400X

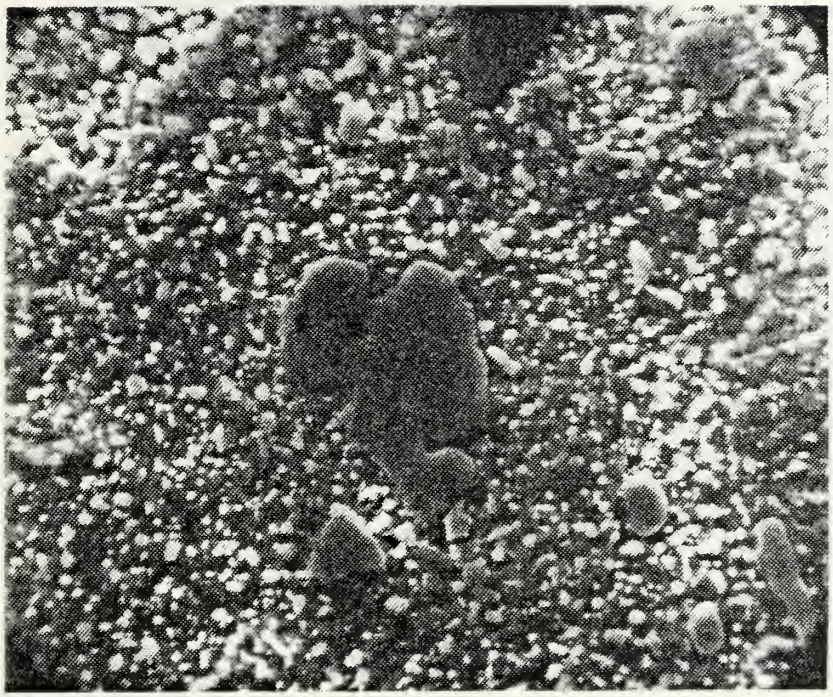

Fig. 19 As-received material showing residual carbides on a background of temper carbides. Magnification 2400X

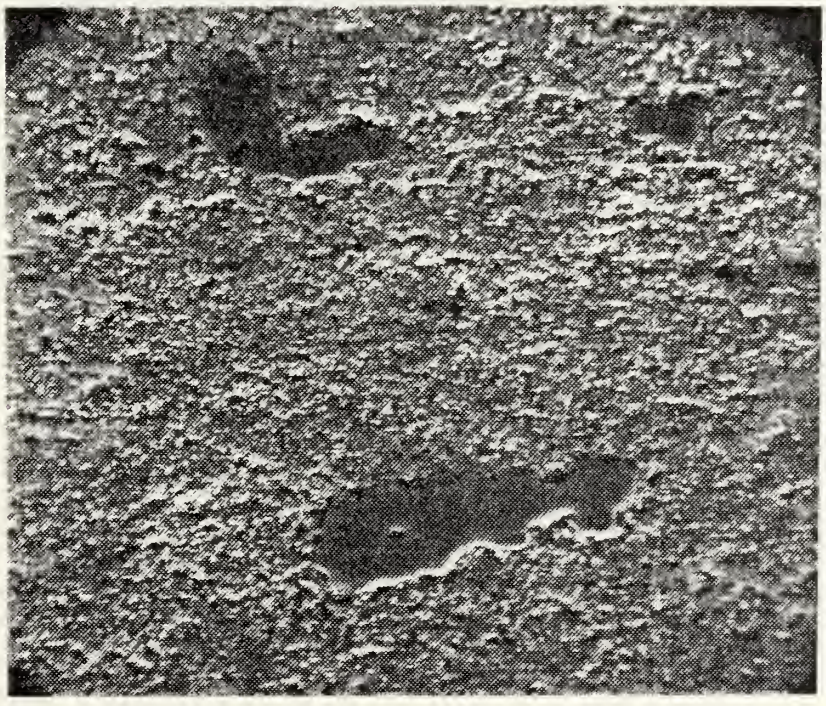

Fig. 20 Material austenitized at 1150°C for five hours, warm-rolled at 650°C. Magnification 2400X

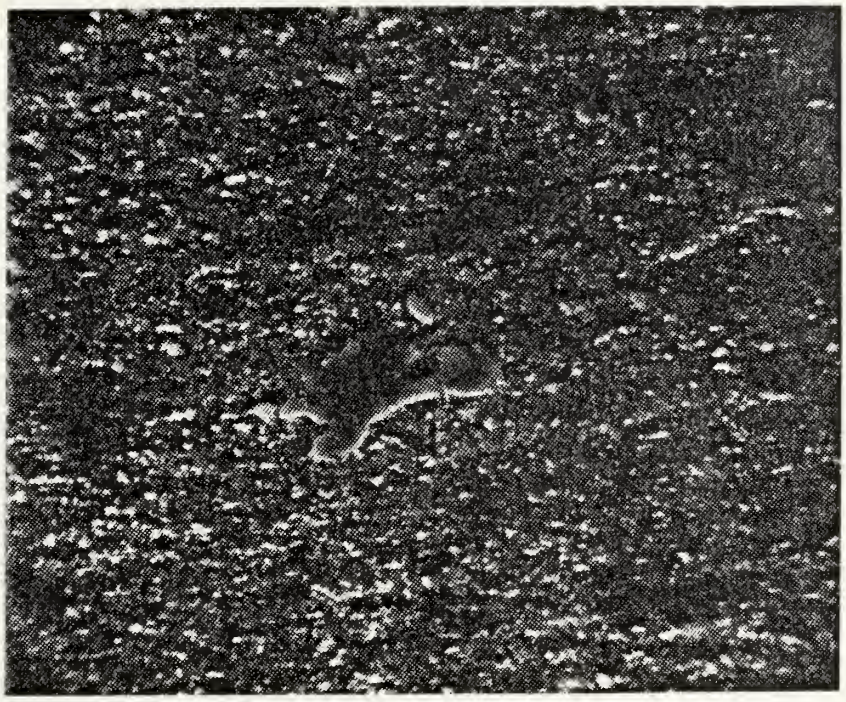

Fig. 21 Material austenitized at 1150°C for five hours, warm-rolled at 700°C. Magnification 2300X

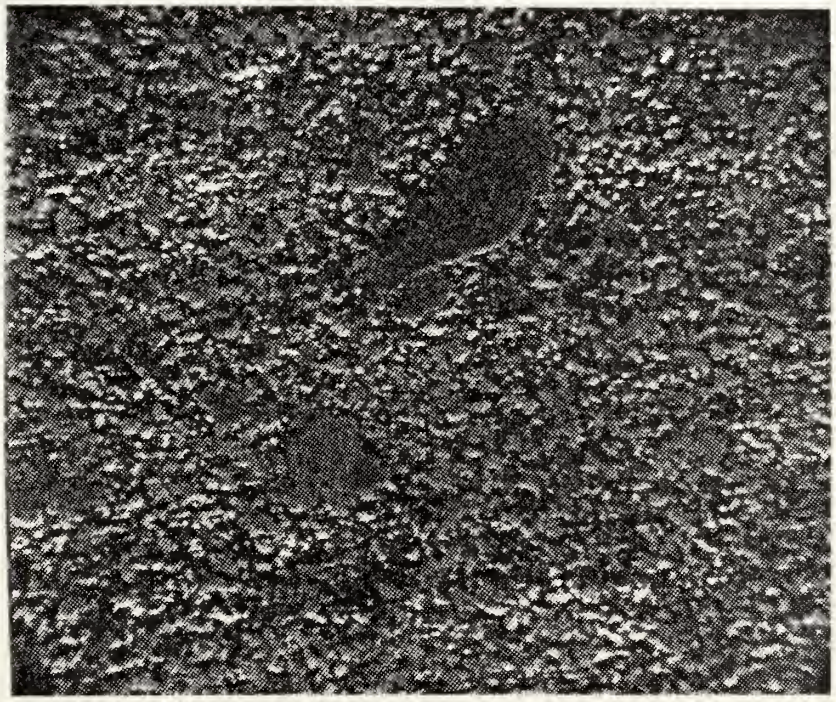

Fig. 22 Material austenitized at 1150°C for five hours, warm-rolled at 750°C. Magnification 2200X

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